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INTENSE PROTON BEAM CURRENT MEASUREMENT VIA PROMPT GAMMA RAYS F--ETC(U)
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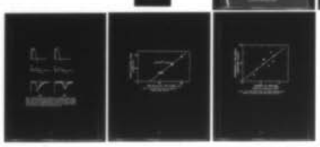

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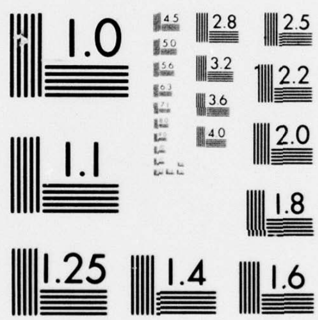

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NRL Memorandum Report 3731

Intense Proton Beam Current Measurement via Prompt Gamma Rays from Nuclear Reactions

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March 1978

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Washington, D.C.

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NRL-MR-3731 ~~NRL Memorandum Report 3731~~	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) INTENSE PROTON BEAM CURRENT MEASUREMENT VIA PROMPT GAMMA RAYS FROM NUCLEAR REACTIONS		5. TYPE OF REPORT & PERIOD COVERED Interim report ~~on a continuing NRL problem~~.
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) J. Golden, R. A. Mahaffey, J. A. Pasour*, F. C. Young and C. A. Kapetanakos		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Research Laboratory Washington, D.C. 20375		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS ~~NRL Problem H02-28A~~
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research Arlington, Virginia 22217		12. REPORT DATE Mar[redacted]78
		13. NUMBER OF PAGES 15 p.
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) 18 SBIE 19 AD-E000 146		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

14 6 9 11 12

16. DISTRIBUTION STATEMENT (of this Report)

~~Approved for public release; distribution unlimited.~~

10 Jeffery Golden, Redge A. Mahaffey, John A. Pasour, Frank C. Young Christos A. Kapetanakos

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

This research was sponsored by the Office of Naval Research and the Department of Energy.

*NRC Research Associate at the Naval Research Laboratory.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Plasma physics
Relativistic electron beam technology
Intense ion beams
Plasma diagnostics

gamma

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The current of an intense, pulsed proton beam is experimentally determined by monitoring prompt γ rays from nuclear reactions induced in a suitable target. Relevant data is given on the reactions employed including ^{7}Li(p,γ)^{8}Be, ^{19}F(p,αγ)^{16}O, and ^{12}C(p,γ)^{13}N so that absolute currents can be determined. This method avoids the complication of target blow-off and the need for attenuating screens when applied to high current density beams.

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INTENSE PROTON BEAM CURRENT MEASUREMENT VIA PROMPT GAMMA RAYS FROM NUCLEAR REACTIONS

I. INTRODUCTION

Intense, pulsed ion beams with current density ≥ 1 kA/cm^2 have been generated by reflex tetrodes,[1] reflex triodes,[2,3] and pinched electron beam diodes.[4] In addition, pulsed ion beams of lower current density, i.e., ≥ 0.1 kA/cm^2 have been produced by magnetically insulated diodes.[5,6] In many of these investigations, the beam current was inferred from the number of ions per pulse determined by nuclear activation analysis[7] of a suitable target after the shot, and the temporal shape of the ion pulse, which usually was obtained with scintillator-photodiode detectors.[2,4]

At high current densities, this diagnostic method becomes complicated because it requires the use of metal screens with known transmission to attenuate the beam in order to avoid ablation of the target. Similarly, the beam must be attenuated before striking the scintillator-photodiode detector in order to avoid distortion of the pulse shape from the heating, quenching and saturation of the scintillator. In addition, since the response of the scintillator is a function of the ion energy, a precise determination of the pulse shape requires knowledge of the ion energy distribution.

This report describes a new diagnostic method to measure the current of intense proton beams by detecting the prompt γ rays emitted from nuclear reactions induced in a target by the beam. The present diagnostic can be used at high current densities without the complication of attenuating screens.

Note: Manuscript submitted February 10, 1978

II. DIAGNOSTIC METHOD

When an intense ion pulse strikes a suitable target, nuclear reactions occur which emit radiation promptly, that is, within a time interval much shorter than the ion pulse duration. The prompt radiation may include γ rays, charged particles, or neutrons. By monitoring the prompt radiation pulse, the rate at which ions strike the target can be determined provided the yield of the nuclear reaction and the calibration of the prompt radiation detector are known. The detector's calibration can be obtained at current densities for which blow-off is not important using a target in which both prompt radiation and residual radioactivity are induced by the ion beam. Analysis of the residual radioactivity provides the number of ions in the pulse which is used to normalize the prompt γ-ray signal. If the prompt radiation and the residual radioactivity are not produced by the same reaction, then reactions should be chosen which have resonance energies that are nearly equal or the energy distribution of the ion pulse must be otherwise known. For example, in Li_2CO_3 targets, the reaction $^{12}C(p,\gamma)^{13}N$ which is responsible for the residual radioactivity has a resonance at 457 keV that is near the resonance energy of the $^{7}Li(p,\gamma)^{8}Be$ reaction that produces most of the prompt γ rays.

Nuclear reactions which produce prompt γ rays are selected so that simple monitoring devices such as scintillator-photomultiplier detectors can be used. Because the ion pulse is usually accompanied by an intense flux of bremsstrahlung, extensive shielding is necessary to attenuate the x-ray signal. If the bremsstrahlung photon energy is ≤ 1 MeV, it is advantageous to use reactions which emit higher energy γ rays. Then the bremsstrahlung flux can be attenuated to a lower level than the γ-ray

pulse by a lead shield. If the x-ray signal cannot be eliminated by shielding, this diagnostic may still be used, but the target must be located so that the ion pulse does not strike the target until after the bremsstrahlung pulse has ended.[7] Then a gated detector can be used to monitor the prompt γ rays.[7,8]

If the γ-ray energy is multi-MeV, interactions in the lead shielding produce a secondary spectrum of lower energy γ rays which can be efficiently detected with an organic scintillator of modest size. However, as a consequence of the γ-ray interaction with the shielding, the detection efficiency is highly sensitive to the placement of the shield, detector and target.

III. EVALUATION OF REACTION YIELDS

To maximize the nuclear reaction yield, resonant reactions and thick targets are used. Three such reactions which have been used are listed in Table I. This table includes laboratory resonance energies E_R, widths Γ, and emitted γ-ray energies E_γ for each reaction. These values are taken from the compilations of Ajzenberg-Selove and Lauritsen.[9] Also listed is the total yield ΔY_∞ of each resonance for a thick target of composition indicated in the table, and the total thick target yield between resonances Y_∞.

The thick target yield for the 441 keV resonance of the ^{7}Li(p,γ)^{8}Be reaction is reported by Fowler and Lauritsen.[10] The thick target step for the 1.03 MeV resonance is determined from that for the 441 keV resonance by using the radiation widths $\omega\Gamma_\gamma$ determined by Kraus[11](1.03 MeV) and by Fowler and Lauritsen[10](0.441 MeV). It should be noted that the ^{7}Li(p,p$'\gamma$)^{7}Li reaction is also resonant at 1.03 MeV but not at 441 keV. The ΔY_∞ for this reaction is much larger than for the (p,γ) reactions, but it produces γ rays with an energy of 478 keV.[9,10,12]

The $^{19}F(p,\alpha\gamma)^{16}O$ is resonant at many energies below 2 MeV.[9] The ΔY_∞ listed in Table I are based on values reported by Chao, Tollestrup, Fowler and Lauritsen[13] for thick CaF_2 targets which have been converted to CF_2 (Teflon) targets using stopping cross sections from Whaling.[14] Using this reaction to determine the current of an intense pulsed proton beam requires knowledge of the energy distribution of the protons; except however, in the ranges 345-550 keV, 680-860 keV, and 1.390 - 1.640 MeV, the thick target yields vary by less than 30%.

The thick target yields for the $^{12}C(p,\gamma)^{13}N$ reaction have been measured by Seagrave.[15] Also, possibly useful reactions not discussed here are the $^{27}Al(p,\gamma)^{28}Si$ and $^{13}C(p,\gamma)^{14}N$ reactions.[10,16]

IV. EXPERIMENTAL DEMONSTRATION

The current of a proton beam has been measured as an experimental demonstration of this diagnostic method. The proton beam is generated by a reflex tetrode[1] powered by the SOL generator at the Naval Research Laboratory. A schematic of the experimental apparatus is shown in Fig. 1. The reflex tetrode is operated with a 5 cm OD cathode K, a 6.25 μm thick aluminized Mylar first anode A_1, and a 12.5 μm thick polyethylene second anode A_2. The cathode-anode gap K-A_1 is 1.7 cm and the A_1-A_2 gap is 5 mm. The applied potential V, corrected for voltage across the load inductance, is the range 390-480 kV with average total currents of 2-6kA. The applied axial magnetic field is 5.6kG.

A thick target 13 cm in diameter and made of carbon, Teflon (CF_2), or lithium carbonate (Li_2CO_3) is mounted on an aluminum plate which is grounded to the wall of the stainless steel vacuum chamber. The axial positions of the target are chosen to be adjacent to gaps between magnet

coils so that the monitored γ-ray flux is not attenuated by the coils. Located at 40 cm from the target is a 5 cm diameter, 7.5 cm long cylinder of Pilot-B scintillator coupled to an RCA 8575 photomultiplier. Both are enclosed within a 5 cm diameter cavity inside a 15 cm x 15 cm x 50 cm lead shield. Additional lead shielding is used so that a thickness > 10 cm surrounds the detector on all sides except between the scintillator and the target. In this direction the lead is 5 cm thick. Attenuation of bremsstrahlung by the shielding is tested by comparison of photomultiplier signals for shots with and without targets. The signal is < 10mV when the target is absent. With Teflon or Li_2CO_3 targets, the signal amplitudes are on the order of one-tenth of a volt, and with carbon targets, the signal is a few millivolts for proton currents ~ 1kA. Signals obtained with a Teflon target are presented in Fig. 2. The thickness of lead between detector and target is varied, and the signal attenuation is found to be consistent with multi-MeV γ rays being monitored.

Further evidence that the observed photomultiplier signals are produced by γ rays from reactions in the target is provided by two independent tests. First, because of the proton time-of-flight, the γ-ray signal is observed to occur later in time relative to the voltage pulse as the Teflon target is positioned further from the second anode A_2. This time delay is illustrated in Fig. 2. The results of a series of measurements are presented in Fig. 3, where the time delay between the beginning of the applied voltage pulse and the beginning of the photomultiplier signal is plotted for different target positions. The time-of-flight corresponds to a velocity $\approx 8 \times 10^8$ cm/sec and indicates

a proton energy of 0.4 MeV which is consistent with the applied potential. The abscissa intercept of 28 nsec in Fig. 3 is attributed to the time delay of the photomultiplier.

In a second experimental test, a Teflon target is used and the time integrated γ-ray signal is compared with $N_p(E \geqslant 340)$, the number of protons having an energy $\geqslant 340$ keV. The operating characteristics reported previously[1] are used to obtain $N_p(E \geq 277)$ from the peak applied corrected potential V and the total current averaged over the time τ_{277} when $V \geq 277$ keV (= E_R of the $^{14}N(p,\gamma)^{15}O$ reaction). Then $N_p(E \geq 340)$ is estimated to be $\tau_{340}\ N_p\ (E \geqslant 277)/\tau_{277}$. In Fig. 4 the time integrated γ-ray signal is seen to be proportional to $N_p(E \geqslant 340)$. Because $V \leqslant 484$ keV, it is concluded that the γ-ray signals are produced predominantly by the $^{19}F(p,\alpha\gamma)^{16}O$ reaction at the 340.5 keV resonance. This is further supported by the observation, based on the residual radioactivity due to $^{12}C(p,\gamma)^{13}N$ reactions in the target, that less than 10% of the protons in the pulse have energies $\geqslant 457$ keV. Moreover, it is found that the number of ^{13}N decays is also proportional to the integrated γ-ray signal.

V. SUMMARY

A method has been developed for determining the current of an intense ion beam via the prompt γ-rays from nuclear reactions. The current measurement is estimated to be accurate to within a factor of two. The diagnostic can be applied to proton beams with currents $\geqslant$ 1kA and energies $\geqslant$ 0.4MeV, e.g., using the reactions with ^{19}F and ^7Li. Furthermore, prompt γ-rays have been observed from the $^{12}C(p,\gamma)^{13}N$ reaction even with proton currents of only a few kiloamps. This indicates that the $^{12}C(p,\gamma)^{13}N$ reaction may prove useful and convenient at high current and at extremely high current density.

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Table I. Proton induced reactions producing prompt γ rays.

Reaction	E_R (keV)	Γ (keV)	E_γ (MeV)	ΔY_∞ quanta/ 10^8 protons	Y_∞ quanta/ 10^8 protons
$^7Li(p,\gamma)^8Be$	441	12.1	14.7(33%) / 17.6(67%)	1.9	1.9
(Li target)	1030	168	15.25 / 18.15	0.31	2.21
	2060	310	16.12	-	-
$^{19}F(p,\alpha\gamma)^{16}O$	227	1.0	6.7-7.1	0.002	0.002
(CF_2 target)	340	3.3		2.30	2.30
	484	0.9		.71	3.01
	597	30.0		3.57	6.58
	672	6.0		6.35	12.9
	835	6.5		2.65	15.5
	872	4.7		49.0	64.5
	902	5.1		1.98	66.5
	935	8.1		26.5	93.0
	1090	0.7		0.32	93.3
	1140	2.5		1.32	94.6
	1189	110		51.6	146
	1283	18.6		12.2	159
	1348	4.9		18.1	177
	1373	12.4		108.5	285
	1694	35		-	-
	1949	40		-	-
$^{12}C(p,\gamma)^{13}N$	457	38	2.37	0.0075	0.0075
	1699	67	3.51	0.0109	0.0184

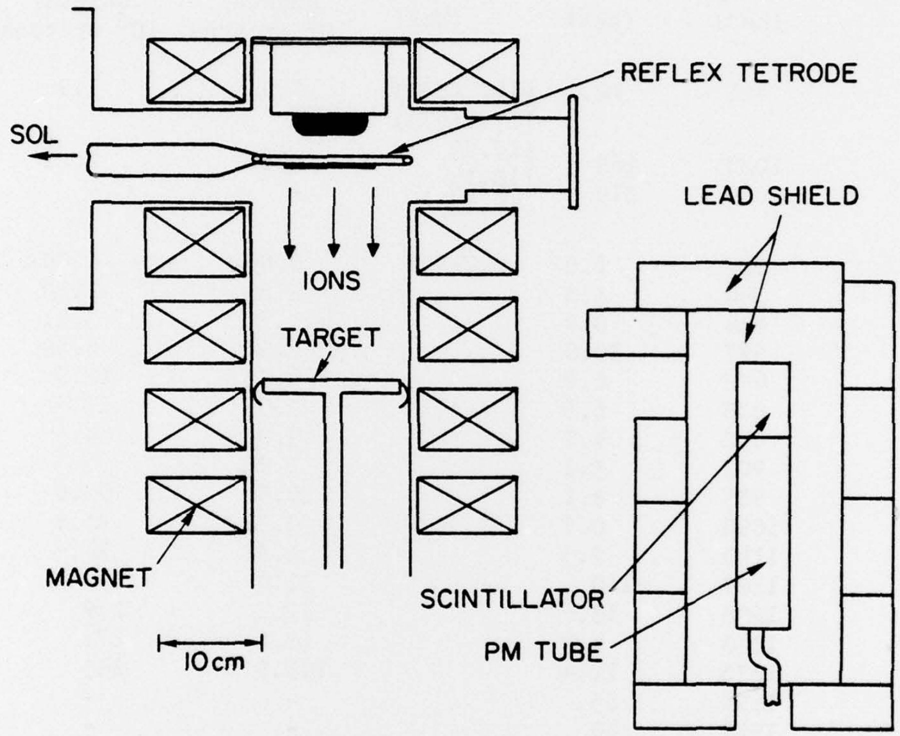
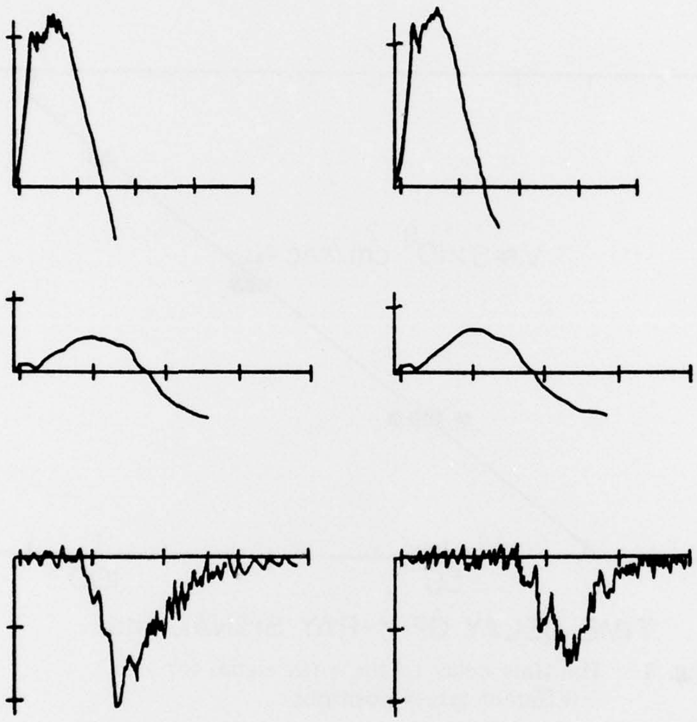


Fig. 1 — The experimental apparatus



(a) (b)

Fig. 2 — Typical oscilloscope waveforms: the applied voltage (upper, 450 kV/div); the total current (middle, 16 kA/div); and the γ-ray signal (lower, 100 mV/div corresponding to 1.3 kA/div of proton current). The time scale for all traces is 40 nsec/div. In (a) the Teflon target is at 19 cm and in (b) at 39 cm from the anode A_2.

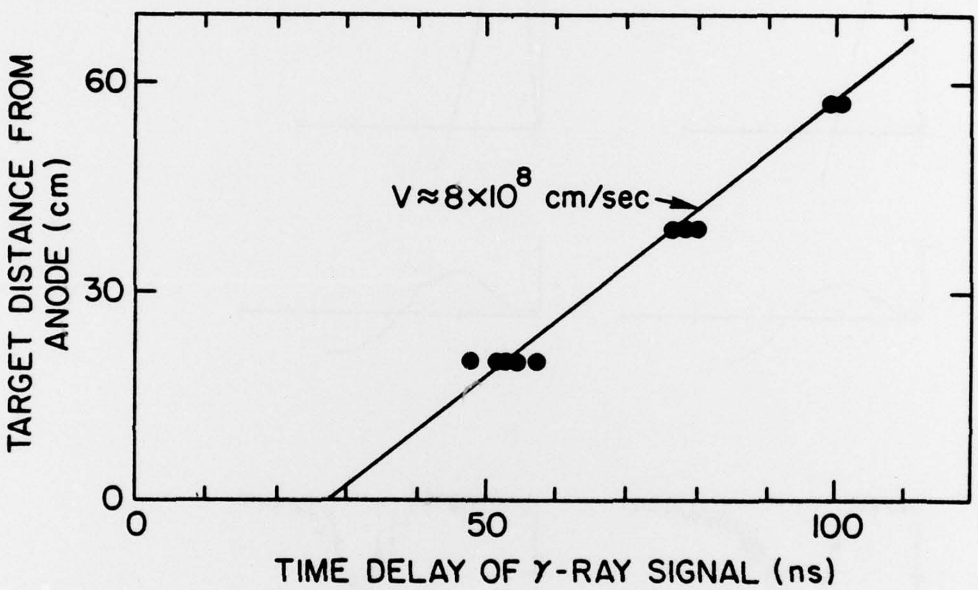


Fig. 3 — The time delay of the γ-ray signal for different target positions

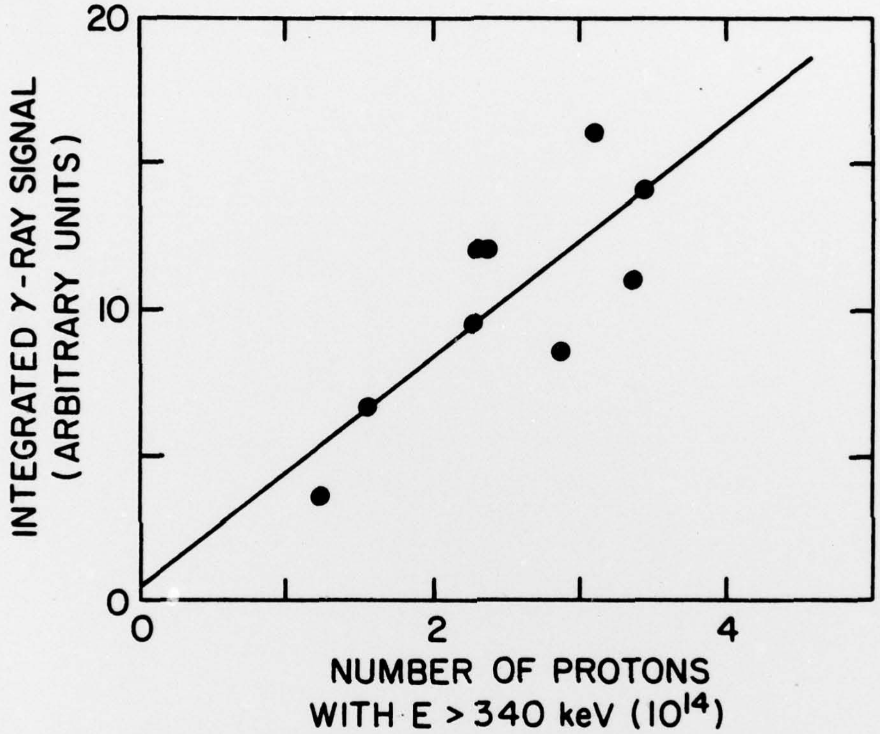


Fig. 4 — The time integral of the γ-ray signal compared to the number of protons per pulse with energy $\geq$ 340 keV